INNOVATIVE EPB-HYBRIDSCHILDTECHNOLOGIE

BEIM BAU DER METRO IPANEMA RIO DE JANEIRO

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ABSTRACT

Pure sands are typically the domain of slurry shields due to their high permeability and their granular characteristics. However, the Earth Pressure Balanced (EPB) shield machine technology has advanced in recent years with improved conditioning agents and shield machines that are equipped with slurry injection facilities and alternative mucking methods. These new so-called hybrid EPB machines have steadily increased the range of application of the EPB technology.
The contribution discusses the capacities and operational features of hybrid EPB vs. slurry shield technology in pure sands. At the example of the Metro Line 4 in Rio de Janeiro (Brazil), the contribution shows that hybrid EPB tunneling in pure sands is possible and it is compared with a state-of-the-art slurry shield project as the KASIG project in Karlsruhe (Germany). Furthermore, the control of the support pressure by means of foam conditioning and slurry injection in conjunction with a close, real-time monitoring of machine parameters is discussed.

INTRODUCTION

Slurry shield and EPB technologies have both undergone significant developments in recent years, leading to the use of parts of one technology in the other and even to completely hybrid systems. Also the ranges of application (see recommendations by DAUB (DAUB 2010)) of both technologies have been shifted far beyond their original limits and are largely overlapping by now. Nevertheless, the basic principles of face support remain unchanged.

Exploiting the possibilities of process data analysis (Maidl 2014), the interactions between the ground and the shield machine are a matter of research and have been intensely investigated.

PRINCIPLES AND CALCULATION OF FACE SUPPORT PRESSURE

Figure 1 shows the principles of two approaches for the determination of required support pressures: kinematic methods and numerical methods.
Kinematic methods that are employed for the assessment of face stability only consider the situation in front of the TBM. The required face support force is determined by means of an assumed failure wedge that would form in ultimate limit state. Based on the ground properties, the vertical surcharge and the self-weight is transformed into a horizontal force along a virtual sliding surface. This horizontal force is

to be balanced by the face support. The calculation results are amended by respective partial safety factors for water and earth pressure and the method-specific support pressure fluctuations are added.

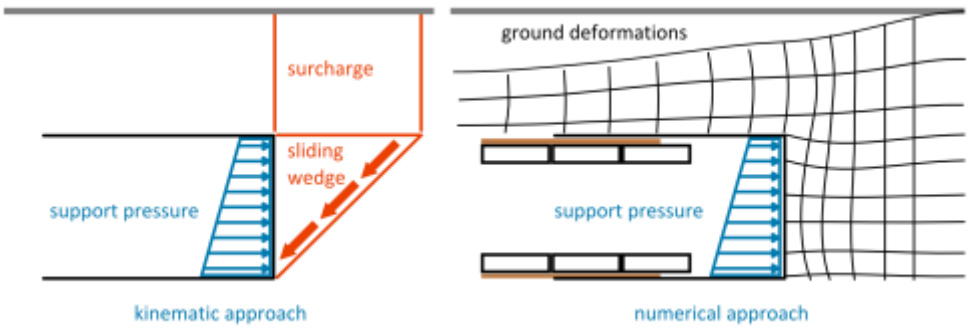

Figure 1. Determination of required support pressures based on kinematic (left) and numerical approaches (right)

However, kinematic methods do not consider the ground deformations and, hence, settlements during passage of the TBM. These are predominantly caused by deformations directly above and behind the TBM. The vertical equilibrium is only considered for the surcharge on the failure wedge. For the complete system that especially needs to be taken into account for the estimation of settlements, kinematic methods do not provide sufficient information.

Numerical methods, contrariwise, are suitable for the determination of deformations if sufficient information on the ground behavior is available and the excavation process is properly modeled. For analyses of the ultimate limit state, however, numerical methods are less suitable since numerical simulations tend to become unstable in the vicinity of the limit state.

Shield urban tunneling, such as the case studies presented in this article, require both stability as well as deformation analyses, so generally both methods are used.

Transfer and control of the face support to the face in slurry shields (SM-V4)

The face support in slurry shields is carried out by the bentonite slurry suspension that fills the excavation chamber. The slurry forms a filter cake on the tunnel face that seals the face and allows to transfer the existing pressure in the chamber onto the soils, namely onto the sand skeleton. Therefore the slurry must comply with particular characteristics in order to be suitable to act as supporting medium. The parameters of slurry that can be adjusted with the slurry mix and tested in laboratory.

The main parameters to be adjusted and controlled in order to assure a safe face support pressure transfer are:

- Density. It can be adjusted according to the sand permeability.
- Yield stress. Shear stress at which the bentonite suspension yields.
- Filtrate baroid. Measure of water loss from the pressurized slurry.
- Sedimentation. Required when using slurries with filler in order to assure that the solid particles of the mix do not sediment in too early.

The actual mechanism of the transfer of the support pressure from the support medium to the soil skeleton is not taken into account by proofs of global stability in slurry shields (Pulsfort 2013). If no or only an insufficient filter cake forms at the tunnel face, it needs to be proven that the dragging forces generated by support fluid penetrating the soil are sufficient to balance the acting forces (DIN 4126 2013). An additional mechanical support as naturally given in EPB shields is not provided by slurry shields.

Slurry shield technology employs a fluid support medium that is pressurized by means of a compressed air cushion in the working chamber (Fig. 2a). According to the principle of communicating pipes, the air pressure is transferred to the support fluid. Depending on the bentonite suspension level in the working chamber, the air pressure and the density of the support medium, the pressure gradient along the tunnel face arises. The pressure of the support medium is thereby measured at the diving wall and typically adjusted based on the reading of the topmost (crown) sensor.

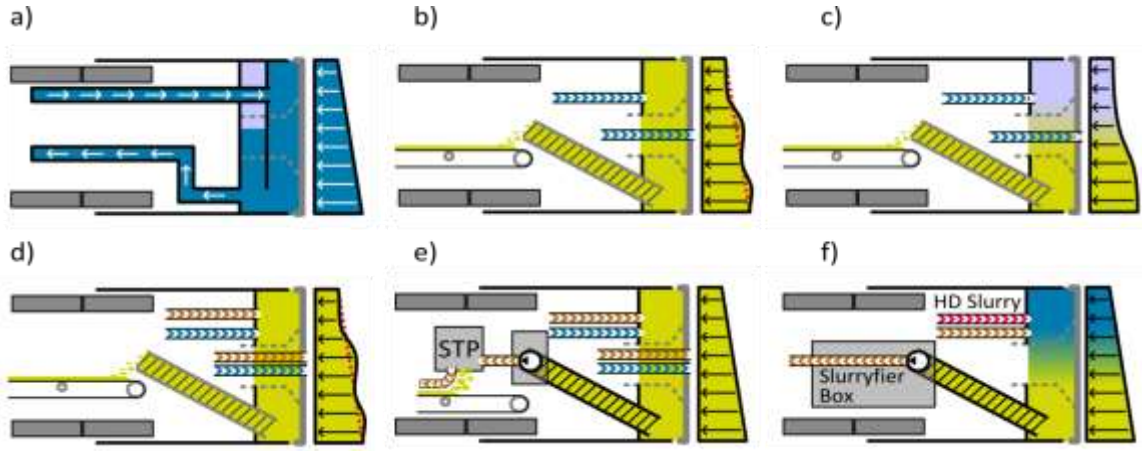

Figure 2.Gradients of support pressure over the tunnel face in different operation modes: a) slurry shield; b) EPB closed mode with polymer/foam conditioning; c) EPB closed mode with excessive conditioning and sedimentation in the excavation chamber; d) EPB closed mode with polymer/foam and slurry conditioning; e) hybrid TBM (Rio de Janeiro type) with polymer/foam and slurry conditioning ; f) hybrid TBM (Kuala Lumpur Variable Density type) with slurryfier box

Rheological properties of the support medium are well-described and can be precisely controlled. For this reason, the controllability of the support pressure is usually regarded superior in slurry shields compared to the EPB technology. Hence, slurry shields are ascribed a high level of safety in keeping the support pressure on target and therefore control settlements and prevent failure of the tunnel face.

In the stationary case, the support pressure acting on the tunnel face can be determined precisely from the sensor values. During excavation, however, flow-related fluctuations occur in the complete excavation chamber and particularly around the feedline and slurryline intakes. These fluctuations increase with higher viscosity and density of the support medium. Here, the recent tendency towards higher densities (recently increasing from around 12 kN/m³ towards 14 kN/m³) to deal with more permeable face conditions (rock fractures, karst…) has a significant impact.

Considering the achievable accuracy of the support pressure in slurry shields, it needs to be considered that measurements at the diving wall during excavation do not necessarily mirror the actual pressure gradient at the tunnel face. The support pressure may fluctuate heavily, especially around the intakes of feedline and slurryline. Furthermore, flow-related fluctuations are more effective at higher densities.

Transfer and control of the face support to the face in EPB shields (SM-V5)

EPB technology uses the (conditioned) excavated material itself as support medium. The material is conditioned with polymers and foams to transform the excavated muck in an optimum support material. Pressure control is achieved by balancing the excavation rate and the extraction rate of material through the screw conveyor such that the material in the excavation chamber remains at the specified pressure. Pressure controlled is also governed by the conditioning. However, in contrast to slurry technology the exact properties of both the excavated soil and the material in the excavation chamber are neither homogeneous nor precisely predictable. Furthermore, the extraction rate through the screw conveyor is quite sensitive to fluctuations in viscosity, pressure and density. Hence, the EPB technology is usually ascribed a lower level of safety and higher safety margins in the support pressure specifications (ZTV-ING 2007).

Sandy soils are very sensitive to soil conditioning measures. In a density range between 15 kN/m³ to 16 kN/m³ the support pressure control can be precisely carried out via the foam conditioning system. Here, the range of application of EPB shields has been significantly enlarged in recent years (Maidl 1995).

Excessive soil conditioning, however, is risky. In case of too low densities, the support medium may segregate and sediment. As a consequence, a foam bubble forms in the upper part of the excavation chamber. In turn, following the pressure gradient, the earth muck in the bottom part of the excavation chamber is unintentionally compacted. This sedimentation process is reflected in the face pressure distribution (see Fig. 2c).

During standstills sedimentation of the granular soil can occur resulting in a redistribution of densities in the chamber and a face support pressure decrease at the crown that must be compensated by injecting slurry in the excavation chamber or at the cutterhead.

Transfer and control of the face support to the face in hybrid shields (SM-V4-V5)

Hybrid TBM in pumping mode

Hybrid TBMs that employ a mixture of EPB and slurry shield technology are increasingly used in order to enhance the range of application of the respective technology.

For the excavation in loose soils with high pressures, the pumping mode of a hybrid TBM can be used (see Fig. 2e). In this mode, the density of the earth muck is reduced by conditioning with bentonite suspension and foam. To keep the pressure, a pump is installed at the end of the screw conveyor. If the material is subsequently treated by a built-in separation plant, even belt conveyance can be used.

Using this technique, the low density and the buffer effect of the foam allow for a very high accuracy in support pressure control (Maidl 2015). During standstills sedimentation can still occur as in EPB shield technology and it must also be compensated by injecting slurry in the excavation chamber.

Variable Density shield machines

Developed especially for the use in extremely heterogeneous ground or karst conditions, this machine type allows switching directly between EPB and slurry shield mode (Burger 2015). This technology has been used in the MRT excavation in Kuala Lumpur in the karstic limestone stretches. In both modes, the material is extracted from the excavation chamber by means of a screw conveyor. At the rear end of the screw conveyor, a slurryfier box is installed where the earth muck is made pumpable by adding bentonite suspension (Fig. 2f). In cases where belt conveyance is applicable, the slurryfier box can be detached and a belt conveyor can be installed.

This machine type combines the advantages of both EPB and slurry shields and fully covers the combined ranges of application.

CAPACITIES OF HYBRID EPB SHIELD IN PURE SANDS: RIO DE JANEIRO LINE 4 SOUTH

Rio de Janeiro Metro Line 4 South is being excavated with a Herrenknecht hybrid and convertible EPB shield with a diameter of 11.51 m. It was designed as a convertible EPB shield because around 50% of the alignment runs in hard rock gneiss. The rest of the stretch runs in sands.

Figure 3 illustrates the particle size distribution curves that characterize this project. The curves have been separated in two groups of sands that are clearly differentiated along the alignments. From approximately km x to 10+120 the sands consist in approximately a 5%-45%-50%-0% ratio of fine particles, fine sand, medium sands and coarse sands (green curves). In the stretch between km 10+120 to 9+400, the particle size distribution changes with a 0%-20%-75%-5% ratio of fine particles, fine sand, medium sands and coarse sands (orange curves).

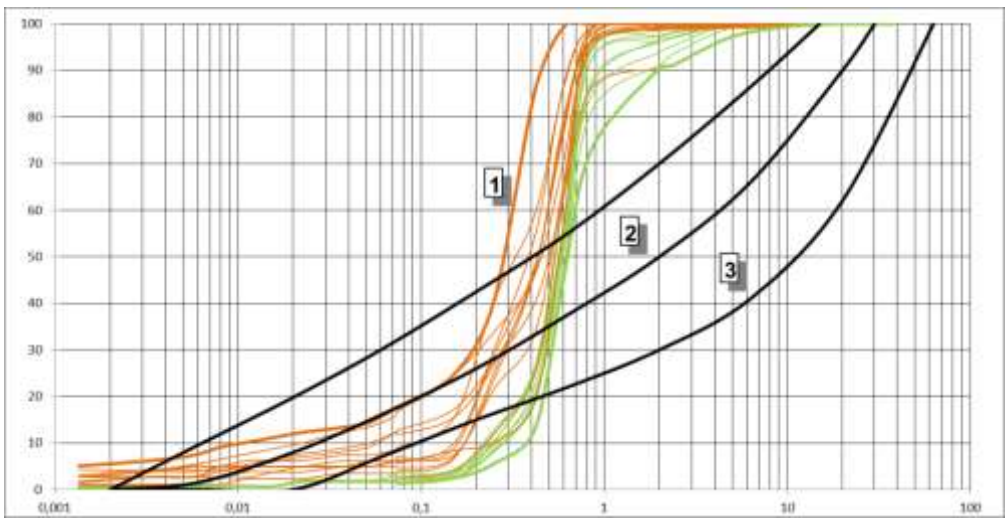

Figure 3. Particle size distribution curves Rio Line 4 with the applicability ranges for EPB shields according to Maidl 1995.

The particle size distribution curves lie outside the typical or even the extended application range for EPB shields. For that reason a hybrid EPB shield was developed for this project that allows operating in the following main modes in sands:

1. EPB mode with foam/polymer conditioning and belt conveyance: conventional EPB operation in closed mode with full chamber. This is the operation mode that will be strived for as long as the sands allow for it.
2. EPB mode with foam/polymer and slurry conditioning and belt conveyance.
3. EPB mode with foam/polymer and slurry conditioning and pumping conveyance. The hybrid EPB is equipped with a pump conveyance system and pipelines at the rear part of the screw conveyor (Figure 4). A small separation plant (Figure 4) is installed on the back-up gantries that allows to separate the sand for belt conveyance whilst part of the remaining slurry can be

reinjected in the chamber and the rest is pump to the tunnel portal via the waste water pipeline (Maidl 2014), (Maidl 2015).

Along the whole alignment in sands the acting groundwater pressures reached 1.4 bar at the tunnel crown. In order to stabilize the face and minimize settlements face support pressures at the crown range from 1.0 bar to 2.0 bar depending on the overburden and groundwater pressure.

To date it is being possible to excavate the Rio sands in modes 1 and 2. In the finer sands it is possible to work in mode 1 using polymer reinforced foam conditioning. Due to sedimentation in the excavation chamber and subsequent pressure drop during standstills, it is sometimes necessary to inject bentonite during standstill to keep pressures stable above the target value.

Figure 4. Left: : back view of the screw conveyor, pumping pipelines and belt conveyor for open mode. Right: Separation treatment plant on the gantry.

However, excavation in the coarser sands is proving to be closer to the applicability limit of conventional EPB technology. When entering the coarser sands the following phenomena were experienced:

a) Cutterhead torque increase and considerable increase of the muck temperature caused by the higher friction of the coarse sands in combination with the lack of fine particles.
b) Difficulties in controlling the face pressure via the screw conveyor since the muck is more permeable (lack of fines) so there is no effective plug acting on the face or in the chamber or in the screw in order to control groundwater flows. The support pressure control is partly dissipating as pore pressure overpressure and not as effective stress into the sand skeleton.

In particular, the temperature increase has a relevant impact on the shield operation and on the overall shield performance since temperature reaches levels that compelled to reduce penetration in order not to exceed temperature values that can trigger damages on the main bearing sealing. For this reason operation was changed to mode type 2. The injection of slurry in combination with foam at the cutterhead, provides an addition of fine particles that reduces the high friction existing in the coarser sands. This has effectively helped to keep muck temperature continuously under the maximum admissible values.

Furthermore, the addition of slurry at the tunnel face helps to reduce the permeability of the tunnel face and of the overall muck in the chamber and the screw conveyor. This helps to more effectively

transfer the face pressure to the soil skeleton and it consequently improves the face support pressure control.

The conditioning system also allows injecting polymer separately aiming to adsorb water and help creating a water tight plug in the chamber and the screw (Maidl 2015).

OPERATIONAL COMPARISON HYBRID EPB – SLURRY SHIELD

Comparative project KASIG Karlsruhe

The selected reference projects are a light rail tunnel in Karlsruhe, Germany, as example for a slurry shield with a diameter of 9.3 m and Metro L4 in Rio de Janeiro, Brazil representing the EPB technology with a diameter of 11.51 m. The ground conditions in Karlsruhe consist of sands and gravels in medium to dense packing much coarse and more permeable than the Rio sands. Rio sands have a dense to very dense packing. Cover over crown in Rio is comprised between 0,8 x D to 1,2 x D and in Karlsruhe around 1 x D.

Face support pressure fluctuations and control

Based on our two reference projects that are characterized by comparable boundary conditions. It can be shown that both slurry shield and foam/polymer-conditioned EPB can be successfully employed in shallow urban tunnels in loose soils with low settlements.

Fig. 5 shows the plan view with settlement indicators, the geotechnical longitudinal section and the range of support pressures over approx. 400 meters along densely built streets for each project. The

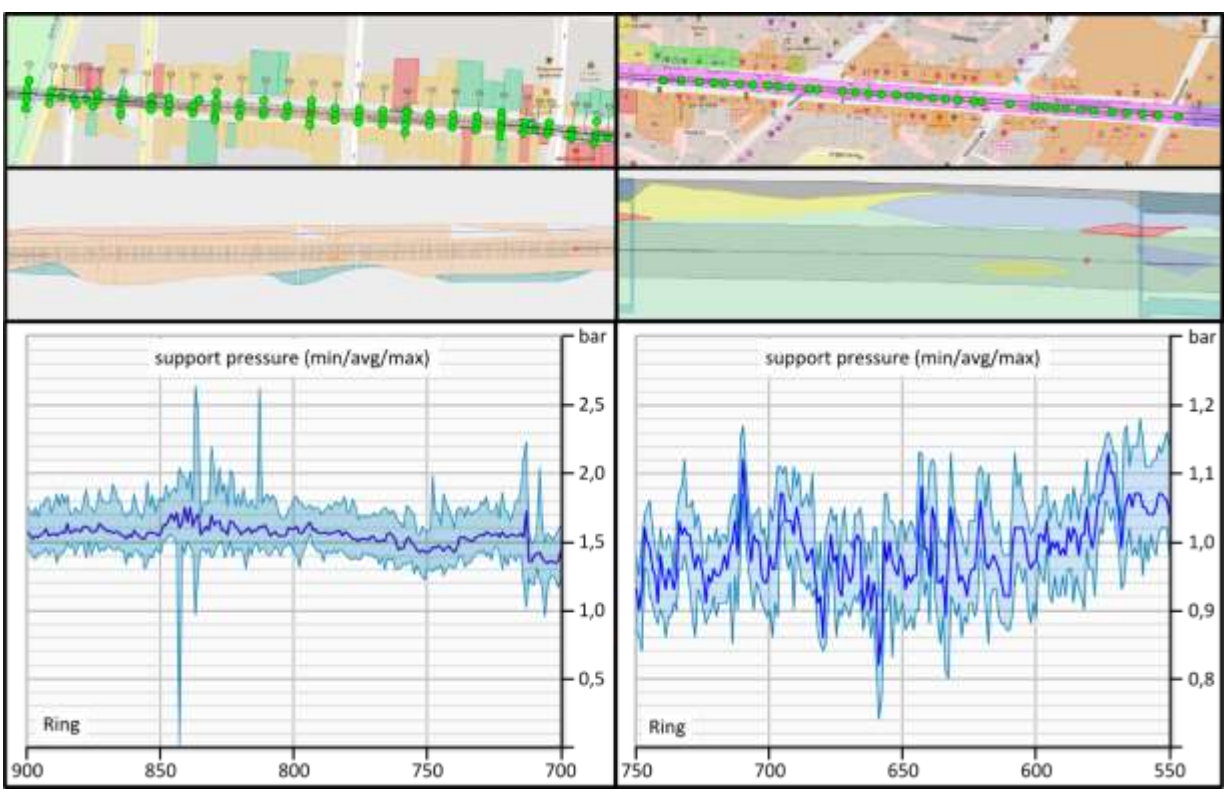

Figure 5.Plan view, longitudinal section and bandwidth of support pressures in the reference projects Rio de Janeiro (hybrid EPB, left) and Karlsruhe (slurry shield, right).

green color of settlement indicates settlements below the alert thresholds of 10 mm in Rio de Janeiro and 8 mm in Karlsruhe.

The Karlsruhe project can be regarded as an example for the state of the art in slurry shield tunneling. Over the full stretch of 2 km, the very shallow tunnel was excavated with extremely low settlements. The fluctuation of measured support pressures was significantly below ±0.1 bar.

The Rio de Janeiro project shows that a modern hybrid EPB shield technology is capable of excavating with comparably low settlements under challenging circumstances of a large diameter (11.51 m) and shallow overburden (approx. one diameter) in sands. The support pressures could generally be kept within a bandwidth of +0.2/-0.1 bar in all phases of the excavation using conditioning measures (see Fig. 5).

Excavation specific energy and advance speed

The concept specific energy represents the energy required during excavation in MJ per m3 of excavated ground. Specific energy can be calculated as shown next with units MJ/m^3:

$$Es = \frac{8 \times T}{P \times D^2}$$

T: torque in MNm

P: penetration m/rev

D: excavation diameter in m

Aiming to equitably compare specific energy in the Rio and Karlsruhe projects, the following adjustment factor to normalize the influence of the diameter difference is made to the specific energy: The cutterhead torque in Rio is multiplied the cubic diameters ratio ($D_{Karlsruhe}^3$ / D_{Rio}^3).

Figure 6 illustrates the average specific energy per ring for the Rio and the Karlsruhe drives respectively for a stretch of 90 rings. Namely, the top diagram shows the Rio data, whilst the bottom diagram of Rio illustrates the adjusted specific energy. Figure 6 also shows the average total TBM thrust and the cutterhead torque per ring for each project.

The following conclusions can be derived:

- Specific energy with EPB technology in coarser sands with no fine particles content (stretch from approx. ring 1200 onwards), doubles the specific energy in finer sands with around 5% fine contents. Adjustments to the conditioning are therefore required in order to reduce specific energy in coarser sand.
- Specific energy in gravel excavated with slurry technology is 5 times smaller than with EPB technology in fine-medium sands and 10 times smaller than EPB technology in coarse sands.
- The difference in specific energy between EPB and slurry shield technology lies in the fact that material in the excavation chamber has a liquid-viscous consistency in contrast to the plastic consistency of EPB muck. Besides the slurry that fills the chamber in slurry shields provides a constant lubrication to the shield reducing its friction while turning. This reduces the cutterhead torque as well as the total thrust considerably (Figure 6.d))
- In particular for the compared projects, the relative density of the gravels in Karlsruhe is lower than the relative density of the Rio sands, which also explains part of the large difference in specific energy between the two projects.

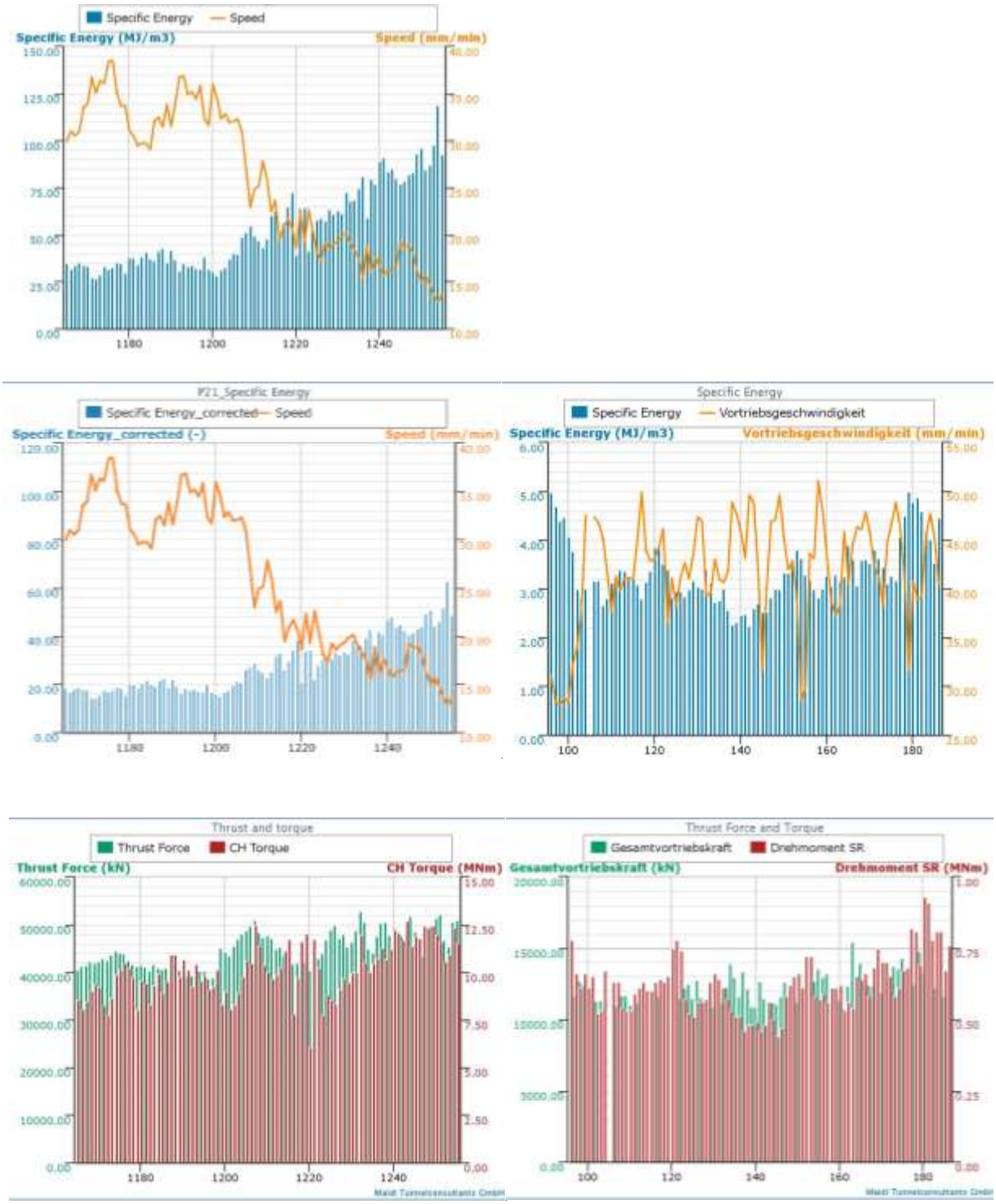

Figure 6. a) Specific energy and speed hybrid EPB shield Rio, b) Corrected specific energy and speed hybrid EPB shield Rio, c) Specific energy and speed slurry shield Karlsruhe, d) Thrust force and cutterhead torque hybrid EPB Rio, e) Thrust force and cutterhead torque slurry shield Karlsruhe

Whilst in specific energy terms the excavation with slurry shield technology is considerably more efficient, the present specific energy analysis does not take into consideration the other processes and the actual consumables involved in the excavation process, such as:

- Energy required to convey the muck out with belt in the case of the EPB shield and pumps in the case slurry shields.
- Energy required for the separation and reutilization of slurry in slurry shield technology.
- Energy required to transport the muck to the dumpsite. Conditioned muck in the case of EPB shields, separated muck in the case of slurry shields
- Total amount of consumables required for conditioning. Foam, polymer and slurry in EPB shields and total slurry consumption in slurry shields.

Illustrating the impact of geology on EPB shield technology, Figure 7 plots specific energy and advance speed when the EPB shield in Rio crossed a 50 m long silt lens. Specific energy reduces to 6 MJ/m^3 and average advance speed increases to over 50 mm/min. These are similar values as the slurry shield in Karlsruhe working in gravel, indicating the specific energy is minimum when each technology works in its predestined geology.

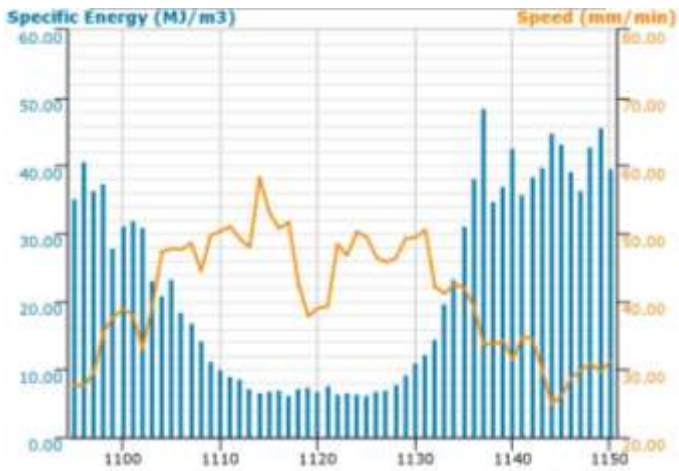

Figure 7. Reduction of specific energy and speed in Rio Line 4 while crossing a silt lens

Cutterhead hyperbaric interventions

One of the critical stages during shield tunneling are the hyperbaric interventions for tool inspection and change. Generally, hyperbaric interventions with slurry shield technology are regarded as safer than with EPB technology since the possibility of using the slurry circuit for the muck-slurry exchange considerably reduces the risk of pressure dropdowns and material loss, whilst also assuring a better quality filter cake. However, hybrid EPB technology equipped with pumping conveyance system has proven in Rio to be a safe manner to prepare and carry out interventions in sands without ground improvement treatments.

Settlement control

In both projects the maximum settlement criteria was respected. The settlement criterium in Karsruhe was very strict since the tunnel runs directly under the urban train tracks in operation. In Rio excavation took place under the street with higher tolerances in the settlement criteria. Therefore in Rio face support and grouting pressures are defined as small as possible targeting a maximum settlement at the surface of 10 mm. In Karlsruhe settlements were generally zero and otherwise always below 2 mm.

CONCLUDING REMARKS

The accuracy of support pressure control principally differs from slurry to EPB shields since the latter does not provide the well-controllable compressed air cushion (Maidl 2012). However, recent developments towards hybrid EPB shields allow this technology to operate at similar accuracies in support pressure control. This is possible by reduction of muck density, friction and permeability by means of a combination of viscous foam, polymer and slurry conditioning. This is being attained even in soil types that typically characterize the application field of slurry shields.

The fact that the excavation chamber is filled with muck of higher density in hybrid EPB shields, compared to slurry shields, provides a higher level of safety such that in case of short-term misoperation the risk of sinkholes as a consequence of a face collapse is reduced, since less material can enter the excavation chamber. Furthermore, due to the better compressibility of (conditioned) earth muck compared to bentonite suspension, pressure fluctuations in the excavation chamber have comparatively less effect on the actual face support pressure.

Finally, in case of the support pressure falling below the acting water pressure, slurry shields face an acute risk of face collapse. In hybrid EPB shields, this risk is lower since the chamber will be still filled with earth muck that provides a residual mechanical support for the tunnel face even if ground water flows in.

Regarding settlement control, the comparable reference projects presented in this paper prove that both shield technologies are suitable for settlement control in granular soils in shallow tunneling.

In future both technologies will likely be further merged. The successful application of hybrid shields in Rio de Janeiro (Hybrid EPB shield) and Kuala Lumpur (Variable Density shields), confirms the assumption that hybrid shields bear an enormous potential. In this context, also the advantages of hybrid machines in terms of muck transportation, separation and recycling of the excavated material should be noted.

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